PREDICTING THE RESPONSE OF SMALL-SCALE NEAR-WALL TURBULENCE TO LARGE-SCALE OUTER MOTIONS

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Abstract The paper deals with the question of how to determine – or "predict" - the near-wall-turbulence statistics from a Reynolds-number-independent, "universal", small-scale signal, and the Reynolds-number-dependent large-scale outer motions in the log layer. An empirical model is proposed, which is intended to take into account the effect of "splatting", not previously considered, thus offering an improved representation of the near-wall-turbulence field.

Background

In a series of experimental studies, extending over a period of some 10 years, Marusic, Mathis, Hutchins and their collaborators (e.g. [1]) have investigated the response of the near-wall streaks in the viscosity-affected sublayer to large-scale outer structures, the latter typically present at a distance of 0.1-0.2 of the boundary-layer thickness from the wall. They show, in particular, that the outer structures affect the near-wall turbulent fluctuations in two ways: by "footprinting" and "modulation", the former being a superposition process and the latter being a more subtle interaction leading to amplification/attenuation of small-scale fluctuations. One particularly notable outcome of this work has been the proposal of an empirical relationship that permits the statistics of the near-wall turbulence to be "predicted", at any Reynolds number, from a "universal" small-scale signal, unaffected by large-scale motions (and thus Reynolds number), and a record of the Reynolds-number-dependent large-scale outer fluctuations in the log-law region. Thus, if the universal signal is denoted u^*, the outer large-scale motions at location y_O^+ are denoted $u_{O,LS}^+$, the empirical relationship for the actual near-wall fluctuations u^+ takes the form,

$$u^+(y^+) = u^*(y^+)[1+\beta(y^+)\theta u_{O,LS}^+] + \alpha(y^+)\theta u_{O,LS}^+ \tag{1}$$

in which α, β are empirical functions, derived from experimental data, and θ in an angle that accounts for the correlation between the large-scale motions at y_O^+ and those at y^+. In the above equation, the latter term represents the superposition (footprinting) process and the former the modulating influence of the large-scale motions.

In a recent PoF paper [2], the present authors have investigated eq. (1) by reference to DNS data for channel flow at Re_τ=1020, and have shown that the symmetric response to high-speed and low-speed large-scale fluctuations, implied by the eq. (1), is not supported by the data. The authors separated large-scale from small-scale motions using a two-dimensional version of the *Empirical Mode Decomposition* of Huang et al. [3], and then extracted the joint PDFs of u^*, v^* (the latter assumed to be the EMD-derived small-scale motion) from eq.(1), subject to α, β given by the originators of eq. (1) for u^*. An example of the analysis, for $y^+ = 13.5$, is given in Fig. 1 (a).

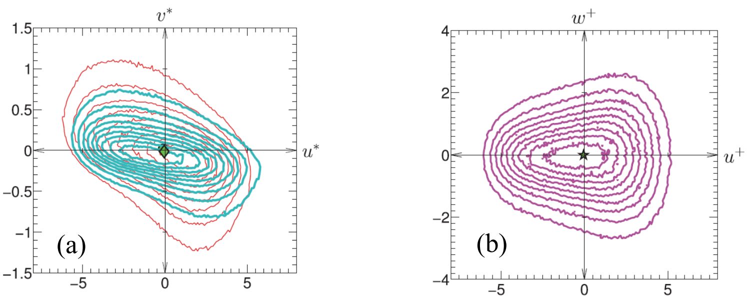

Figure 1. Joint PDFs of velocity fluctuations at $y^+ = 13.5$ from DNS; (a) for "universal" u^*, v^* fluctuations (u^* extracted from eq. (1) and v^* from the EMD small scale) for highly positive large-scale fluctuations (red contours) and highly negative large-scale fluctuations (green contours); (b) for small-scale (*u,w*) fluctuations, illustrating "splatting".

The present authors are of the view that the non-universality displayed in Fig. 1(a) is a likely consequence of "splatting" (sweeps/ejections), implied by Fig. 1(b), and a failure of eq. (1) to take the effects of this process into account. In [3] the authors presented a preliminary alternative to eq. (1), which reduced the differences between the PDFs in Fig. 1(a), thus improving the universality of the $(u*, v*)$ field . In the present paper, the authors pursue this work further, presenting additional statistical data, extracted from the DNS, and extending the model presented in [3]. They also examine, albeit as a minor aspect, the validity of the "Quasi-Steady" model of Chernyshenko et al [4], which is based on the proposition that scaling in eq. (1) should be effected with the local large-scale friction velocity.

Present Contribution

We consider ensemble-averaged statistics, conditioned on large-scale motions. Spatial (*x-z*) snapshots are obtained at various y^+ levels. In each snapshot, domains of positive and negative large-scale fluctuations are identified. Only patches of extreme +/- 10% events within the PDF of the all large-scale motions are considered. Statistics of small-scale motions are then extracted within these patches. This is also the approach underpinning Fig. 1(a).

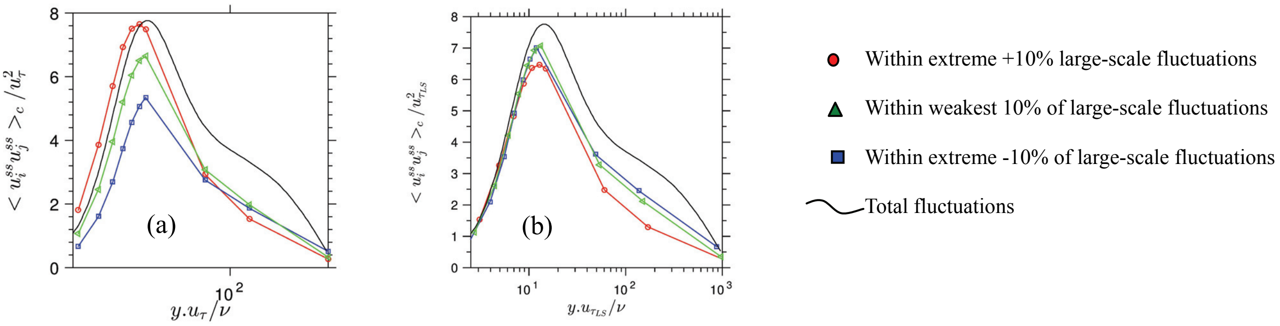

Figure 2. Profiles of streamwise small-scale-fluctuations energy, conditioned on large-scale motions; (a) scaling with mean friction velocity; (b) scaling with local large-scale friction velocity. Black line: total, time-averaged energy.

Fig. 2 gives profiles of the streamwise small-scale intensity, scaled with the mean and local large-scale friction velocity, respectively. Differences among the conditional profiles indicate effects of modulation and splatting only (footprinting is automatically eliminated). Clearly, neither mean scaling nor local scaling renders the small-scale statistics universal, Fig. 2(b) thus contradicting the "Quasi-Steady" universality assumption that underpins some current descriptions.

The phenomenological model proposed herein, in contrast to eq. (1), "predicts" the (instantaneous) velocity field at any y^+ level from the following equation:

$$U_i^+ = u_i^* \times \underbrace{\left(1+\frac{u_{1,LS}}{\langle U_{1,LS}\rangle}\right)}_{\text{modulation}} \times \underbrace{\left(1+\chi_i(y^+)\frac{u_{1,LS}}{\langle U_{1,LS}\rangle}\right)^{-1}}_{\text{splatting}} + \underbrace{\frac{u_{i,LS}+\langle U_{i,LS}\rangle}{u_\tau}}_{\text{superposition}} \qquad (2)$$

in which <…> denotes time-mean value and $\chi_i(y^+)$, to be given in detail in a paper to follow (because of its complexity), is also made to depend on the sign of $(u*, v*)$, i.e. on whether fluctuations are associated with ejections or sweeps. This model, when inverted to yield u_i^*, with all other quantities taken from the DNS data, gives the PDFs in Fig. 3, thus returning a good level of universality for the statistics of u_i^*.

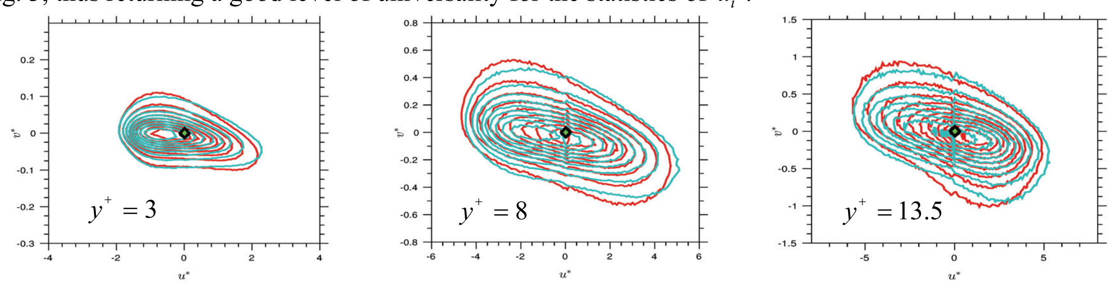

Figure 3. Joint (*u-v*) PDFs of the universal signal u_i^* extracted from eq. (2) at three levels of y^+. Each plot has two sets of contours, one (red) pertaining to regions of extreme 10% positive and the other (green) for regions of extreme 10% negative large-scale fluctuations.

References

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